BOUGUER GRAVITY PROFILES ACROSS THE HIGHLAND-LOWLAND ESCARPMENT ON MARS*

PETER JANLE
Institut für Geophysik der Universität Kiel, F.R.G.

(Received 4 January, 1983)

Abstract. Selected Bouguer gravity profiles crossing the highland-lowland boundary of Mars are calculated. Density-depth models are presented for two areas. All profiles show an isostatic behaviour of the ancient highlands and the adjacent lowlands. Especially isostasy must be implied for the area of the escarpment. It is found that the whole Elysium dome is also nearly in isostatic equilibrium. These geophysical results and additional geological investigations imply a combination of subcrustal and minor surface erosion associated with relatively small vertical isostatic movements of the crust (sinking) in former highland areas. These processes caused a retreat of the highland escarpment of at least several hundred kilometers.

1. Introduction

Since the determination of the martian gravity data by the Mariner 9 and the Viking I and II missions several global analyses of the gravity field have been presented (e.g., Bills and Ferrari, 1978; Lambeck, 1979, Christensen and Balmino, 1979, Phillips and Lambeck, 1980). All these analyses are based on spherical harmonic models of martian gravity and topography. The highest resolution obtained by this method is of twelfth degree and order in gravity (Christensen and Balmino, 1979), i.e. a wavelength of about $\lambda = 1800$ km.

Regional and local model calculations are rare. An investigation of structures in the equatorial region of Phillips *et al.* (1973) and an investigation of regional isostasy of Phillips and Saunders (1975) are restricted to spherical harmonics of $l \leqslant 8$ (i.e. a wavelength of about $\lambda \geqslant 2670$ km). Models of the Tharsis dome of Sleep and Phillips (1979) are based on a gravity field of Sjogren *et al.* (1975) of $l \leqslant 9$.

On the other hand, low altitude gravity data of Viking Orbiter II contain much more regional and also local information in the equatorial region up to a resolution of at least 500 km (i.e. $l \approx 21$; Sjogren, 1979). As global models of harmonics with $l > 10$ of gravity and topography show an increased noise in their power spectra (Christensen and Balmino, 1979), it seems to be more appropriate in the case of regional and local structures to calculate the line-of-sight (LOS) gravity attraction of density models for individual orbits.

A Bouguer gravity map on a global scale from a harmonic model has been published by Bills and Ferrari (1978) but this is restricted to $l \leqslant 10$ respectively $\lambda \geqslant 2100$ km. The aim of this investigation is to present selected LOS Bouguer gravity profiles from low altitude Viking Orbiter II data and to discuss regional anomalies. Especially the

* Contribution No. 254, Institut für Geophysik der Universität Kiel, F.R.G.

The Moon and the Planets **28** (1983) 55–67. 0165–0807/83/0281–0055$01.95.

transitional zone from the ancient southern highlands to the younger northern lowlands will be discussed in this paper.

2. Calculation of Bouguer and Model Gravities

The gravity data for the Bouguer calculations are taken from low altitude line-of-sight (LOS) Doppler gravity observations of the Viking Orbiter II mission (Sjogren, 1979). These data can be considered as LOS free air gravity. The periapsis altitudes of the spacecraft are about 270 km.

As has been demonstrated in previous papers, the gravitational influence of the topography for gravity modelling is very important (e.g. Dvorak and Phillips, 1978, Janle, 1981). The gravity attraction of the topography is calculated as described in Janle (1981). The topographic data are from Topographic Map of Mars 1 : 25 000 000 (U.S. Geological Survey, 1976) and the Atlas of Mars based on topographic maps 1 : 5 000 000 (Batson *et al.*, 1979).

For the construction of the topographic model mean elevations of squares with an area of $4^\circ \times 4^\circ$ between the latitudes of 60° north and south (about 240 x 240 km at the equator) have been determined from the topographic maps. This size of the squares is much less than the approximate horizontal resolution of 500 km. For higher latitudes and higher spacecraft altitudes (more than 1000 km) squares of 5° in latitudinal direction and of 15° in longitudinal direction have been used. The polar areas of the topography have been summarized in two discs.

For the computation of the LOS gravity attraction of the topography the elevation columns have been converted to point masses. Thus, the zero elevation line of the maps mentioned above determines the plane of reduction. A crustal density of 3.0 g cm^{-3} and a mantle density of 3.5 g cm^{-3} has been adopted from Johnston and Toksöz (1977). A slightly reduced density of 2.8 g cm^{-3} has been assumed for the martian topography in contrast to the mean crustal density. A mean crustal thickness of 100 km has been chosen for calculations of crustal density models in accordance with previous papers (e.g., Sleep and Phillips, 1979; Janle and Ropers, 1983).

The LOS gravity attraction of the point mass topography has been calculated with the program ORBSIM described in Phillips *et al.* (1978). The differences between the free air anomalies and the topographic gravity result in the LOS Bouguer anomalies (Figures 2–7).

The accuracy of the observed LOS gravity is rather high (a few milligals (Phillips *et al.*, 1978)). However, the inclusion of the gravity attraction of the topography leads to errors due to inaccuracies of the topographic features in elevation (probable error of 1–2 km according to U.S. Geological Survey (1976)) and horizontal location.

A comparison of USGS and radar derived elevations from earthbased measurements (Downs *et al.*, 1982) yields an agreement of the trends in topographic elevations and nearly the same relative elevations in the Elysium area (Janle and Ropers, 1983). Thus, regional model calculations are justified with the present USGS topography. Regarding the inaccuracy of the topographic data, only gravity anomalies larger than |10| mgal will be considered significant.

3. Interpretation of the Gravity Anomalies

The interpretation of the Bouguer profiles shall be restricted to sections with spacecraft altitudes of less than about 1500 km and regions where the vertical part dominates – i.e. about ±40° north and south of the subearth latitude (φ_{SE}). The latter restriction permits a qualitative interpretation of the anomalies similar to conventional methods in the case of terrestrial presentations of the vertical component of gravity anomalies. For two cases density models of the highland-lowland transition are constructed and the model gravities are fitted to the Bouguer anomalies (Figures 2 and 4).

At first the profile of Revolution 585 will be discussed (Figure 2). It cuts the transitional zone from the ancient southern highlands to the younger northern lowlands nearly perpendicularly and is least disturbed by other topographical and geological units in comparison to the other profiles (Figures 1 and 2). The profile is located at about a longitude of 240° W (= 120° E). It begins in the southern highlands with a mean elevation of 3 km and crosses the transitional zone between 0° and 12° N (Figure 2c). The mean elevation of the adjacent part of Elysium Planitia is about 0 km. As in previous papers the ancient southern highlands will also be called 'continent' (Mutch *et al.*, 1976, p. 210; Coradini *et al.*, 1980) in analogy to the Earth without any more speculations about their genesis. Consequently the highland escarpment will also be named 'continental margin'. The LOS-free air anomalies of +18 mgal of the highland and of −46 mgal just north of the escarpment may indicate a tendency to isostatic equilibrium of the continental margin. The same tendency is shown by the Bouguer anomalies of −50 mgal in the highland area and +40 mgal in the lowland.

Considering now an Airy compensation of the highlands and the lowlands in analogy to the Earth and Moon (excluding the mascon maria), the highland should have an increased crustal thickness and negative Bouguer anomalies. The lowlands of 0 km elevation should have a normal mean crustal thickness and no significant Bouguer anomalies. Thus, the relative high Bouguer anomalies of the lowland area seem to indicate a considerable disturbance of isostasy.

A very simple crustal density model has been calculated to solve this problem. The model consists of a crustal thickening in the highland area of 11.2 km relative to a mean crystal thickness of 100 km. The mass of the thickening is represented by a single disc (IS 1 (= isostatic disc 1) in Figure 1 and Table I). This means a compensation of 2 km of the mean elevation of 3 km of the highland or 66% compensation. Three additional discs for a nearly totally compensated Elysium dome (IS 3–5, Table I, Figure 1) have been introduced in order to account for the influence of the dome ('Elysium dome' stands here for that part of Elysium Planitia with elevations above 0 km). The anomaly of this root model of the Elysium dome is insignificant for this profile because it amounts to only −5 mgal.

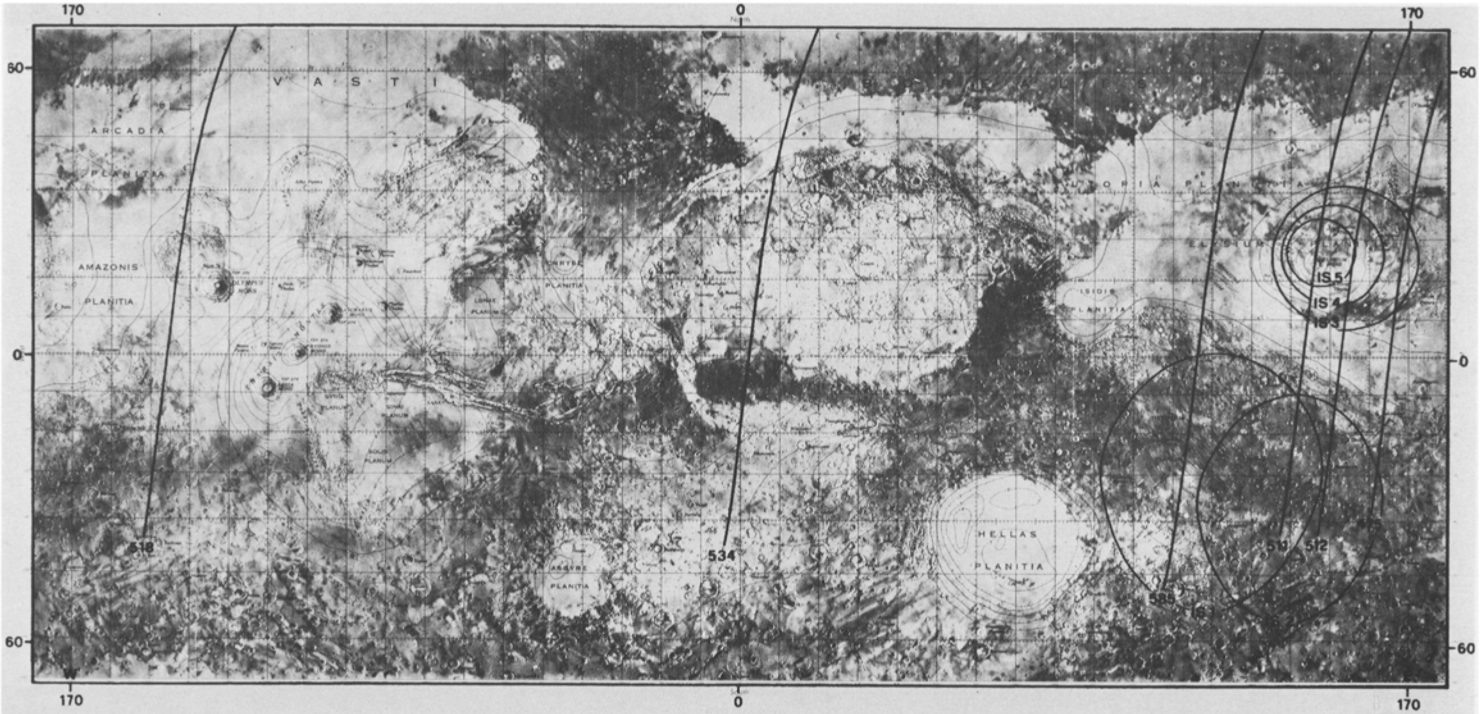

Fig. 1. Topographic map (U.S. Geological Survey, 1976) and locations of the profiles (Viking Orbiter II, Revolutions 475, 511, 512, 518, 534, 585) and of the model discs (IS1–5) of the Figures 2 and 4 (as the southern discs reach high latitudes, they are deformed according to the Mercator projection).

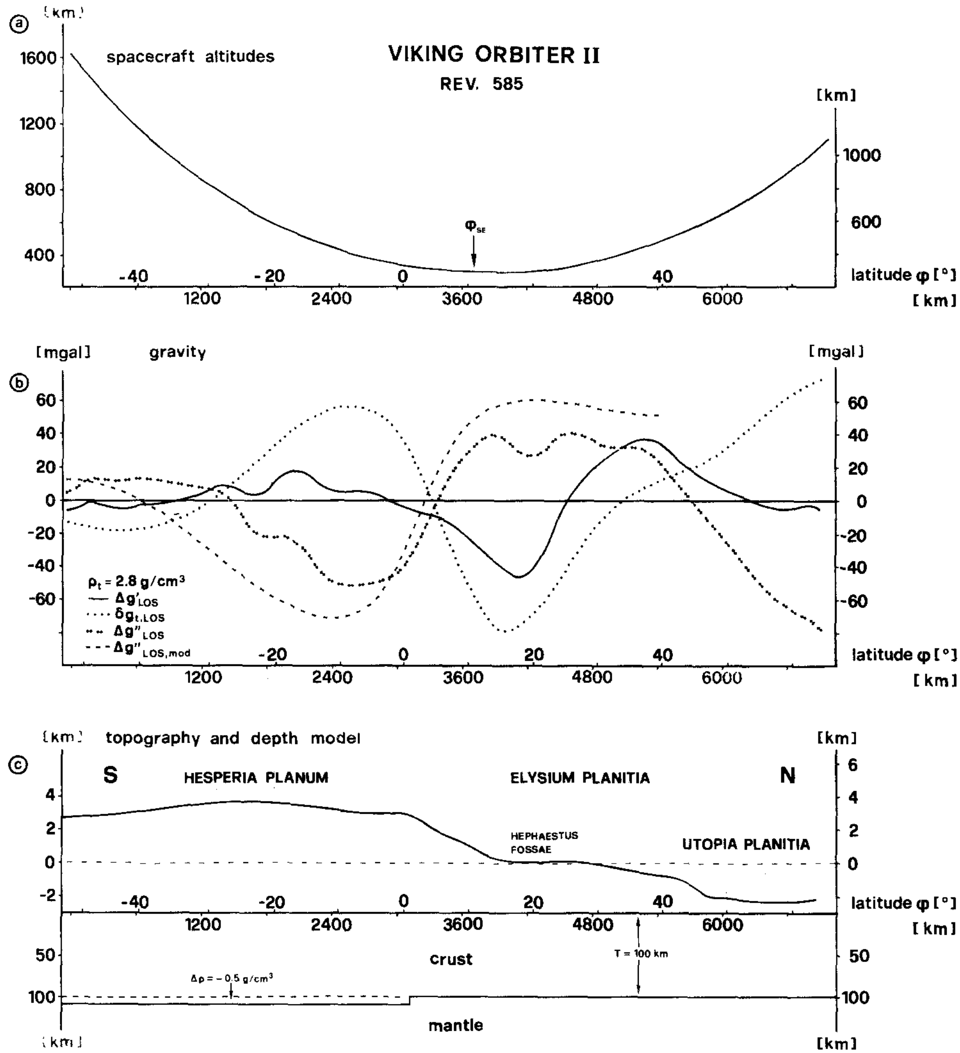

Fig. 2. Hesperia Planum – Elysium Planitia – Utopia Planitia; Viking Orbiter II, Rev(olution) 585. (a) spacecraft altitudes, φ_{SE} = subearth point; (b) LOS gravity anomalies: $\Delta g'_{LOS}$ = LOS free air anomaly; $\delta g_{t,LOS}$ = LOS gravity attraction of the topography; $\Delta g''_{LOS}$ = LOS Bouguer anomaly; $\Delta g''_{LOS,mod}$ = LOS model gravity; ρ_t = density of reduction, plane of reduction is determined by 0 km elevation countour (6.1 mbar plane); (c) topography and density-depth model; $\Delta\rho$ = density difference of crustal and mantle material; T = mean crustal thickness.

As shown in Figure 2, the fit of the model anomaly is not perfect, but the aim of this simple model is to demonstrate only the gross structure of the continental margin. The primary result is that the positive Bouguer anomaly of the lowland area is a boundary effect caused by the crustal thickening of the highland. Thus, the highland-lowland transitional zone shows a tendency to an isostatical behaviour of the continental margin zone.

TABLE I

Model parameters of the discs (IS) of the isostatic compensation models in Figures 2 and 4.

	Radius [km]	Latitude [°]	Longitude[b] [°]	Surface density[a] [g cm^{-2}]	Depth below surface of Mars [km]
IS1	1400	−33.0	140.0	-8.4×10^5	108.4
IS2	1650	−27.0	120.0	-5.6×10^5	105.6
IS3	1000	27.0	155.2	-2.8×10^5	102.8
IS4	700	27.5	152.0	-5.6×10^5	111.2
IS5	450	28.0	149.0	-5.6×10^5	122.4

The models comprise IS1, IS3–IS5 for Figure 2 (Rev. 585) and IS2–IS5 for Figure 4 (Rev. 511) (see also Figure 1).

[a] The surface density is referred to a density difference of crustal and mantle material of -0.5 g cm^{-3}.

[b] Eastern longitudes.

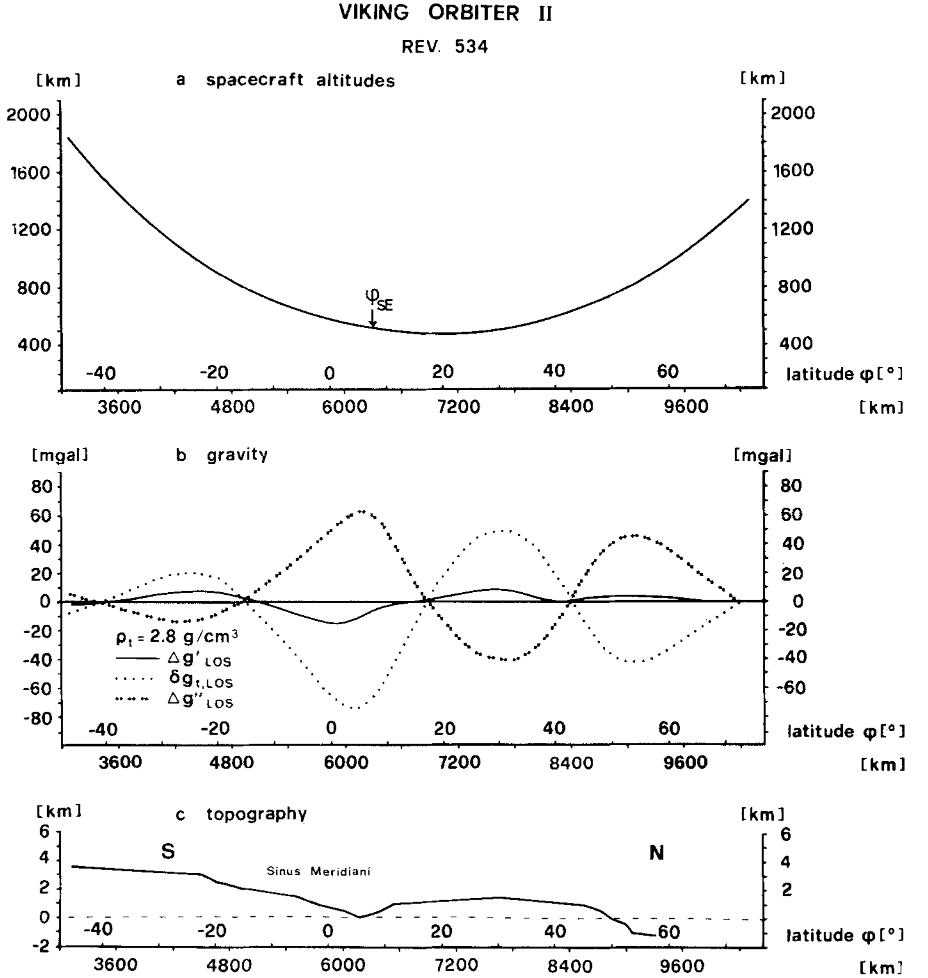

Fig. 3. Sinus Meridiani; Viking Orbiter II, Rev. 534. Detailed description see Figure 2.

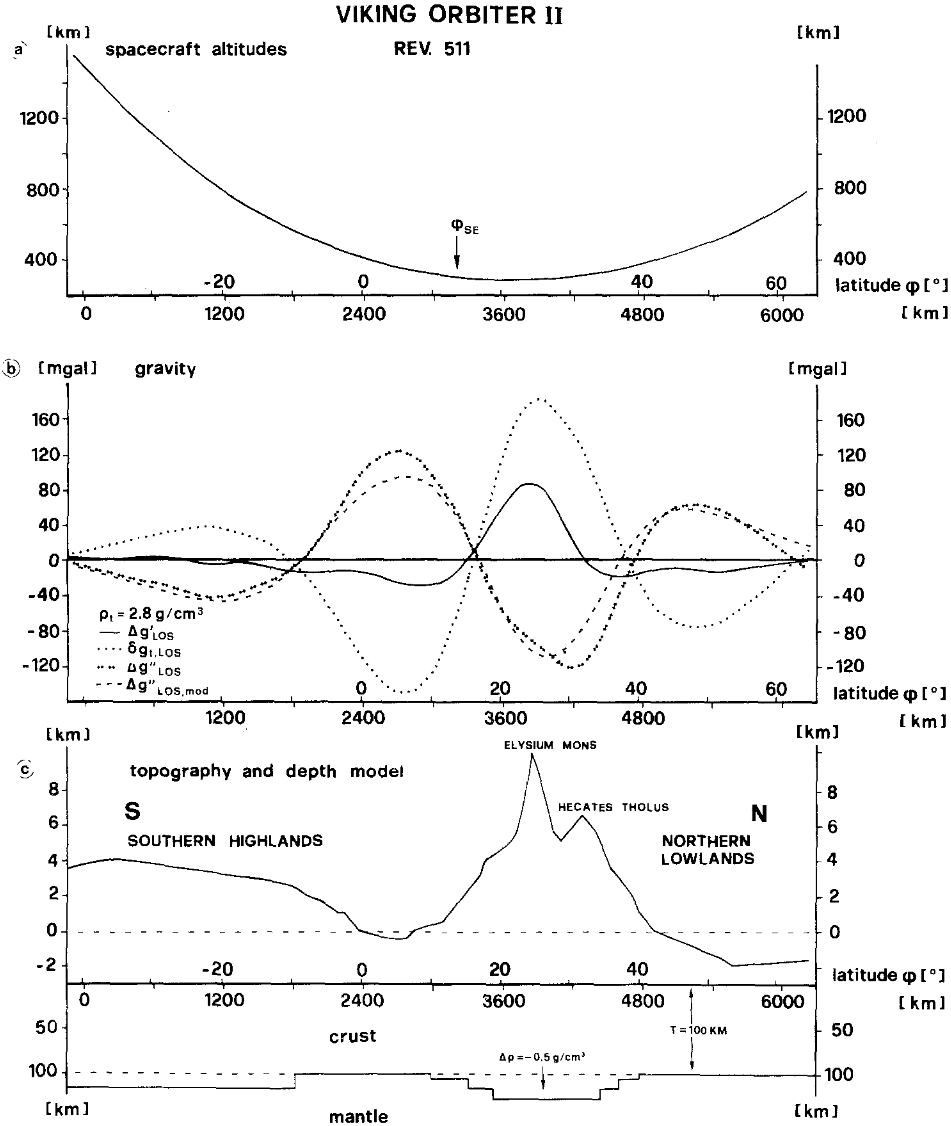

Fig. 4. Elysium dome with Elysium Mons and Hecates Tholus; Viking Orbiter II, Rev. 511. Detailed description see Figure 2.

Figure 3 (Revolution 534, see Figure 1) shows a profile at about 355° longitude W (= 5° E) which crosses Sinus Meridiani at 5° S latitude and reaches the 0 km elevation countour at 50° N. The negative Bouguer anomalies of the highlands north and south of the depression at 7° N with a minimum of −41 mgal indicate an isostatic behaviour of the crust. The large positive anomaly at 7° N may be explained partially by boundary effects of the highlands and partially by the isostatic behaviour of a depression to the

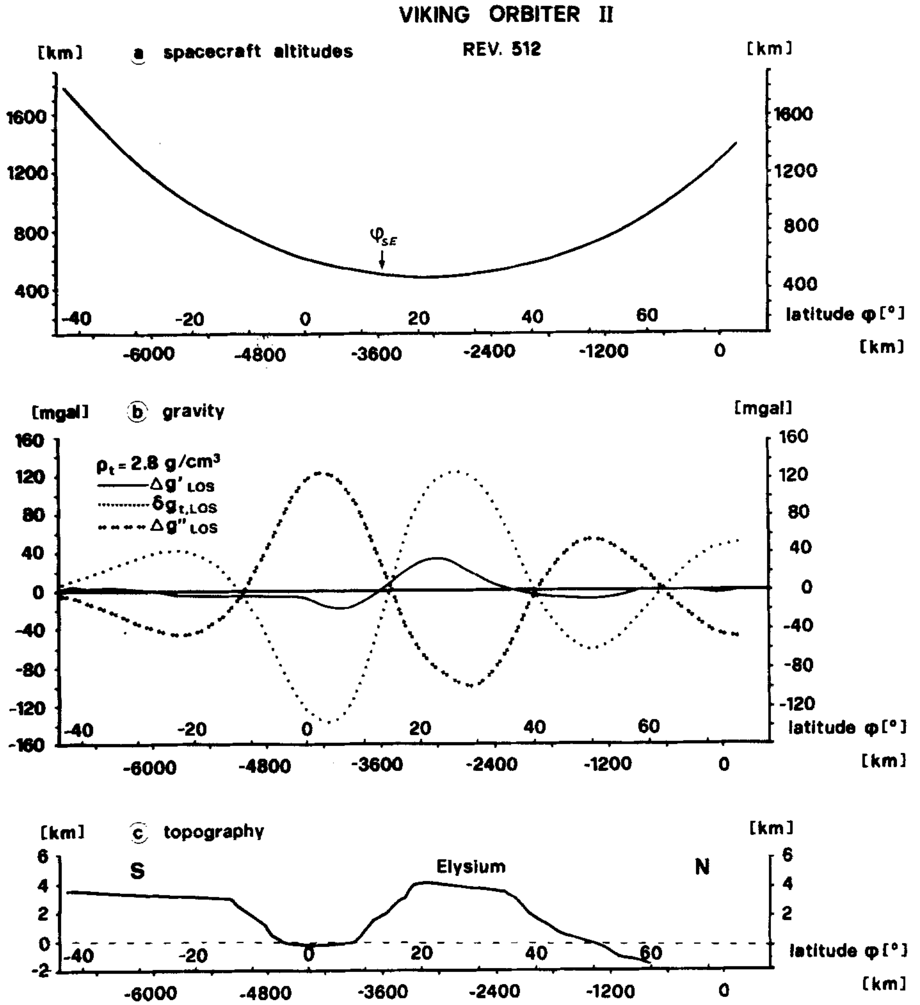

Fig. 5. Elysium dome; Viking Orbiter II, Rev. 512. Detailed description see Figure 2.

west of the profile at 7° N (see Figure 1). The continental margin between 45° to 50° N shows a transition to positive Bouguer anomalies as in the case of Figure 2 (Revolution 585). Thus, the continental margin is also characterized here by an isostatic behaviour.

Revolutions 511, 512, and 475 are located between the longitudes of 180° and 230° W (= 130° E) and cross the Elysium dome (Figures 1, 4, 5, 6). A crustal model has also been calculated for Revolution 511 (Figure 4). It consists of a crustal thickening of 100% isostatic compensation for the highlands (IS2, see Figure 1) and the same crustal thickening model for Elysium as in Figure 2 (97.5% compensation of this root model of Elysium). The general fit here is much better than in Figure 2. No additional fit of the

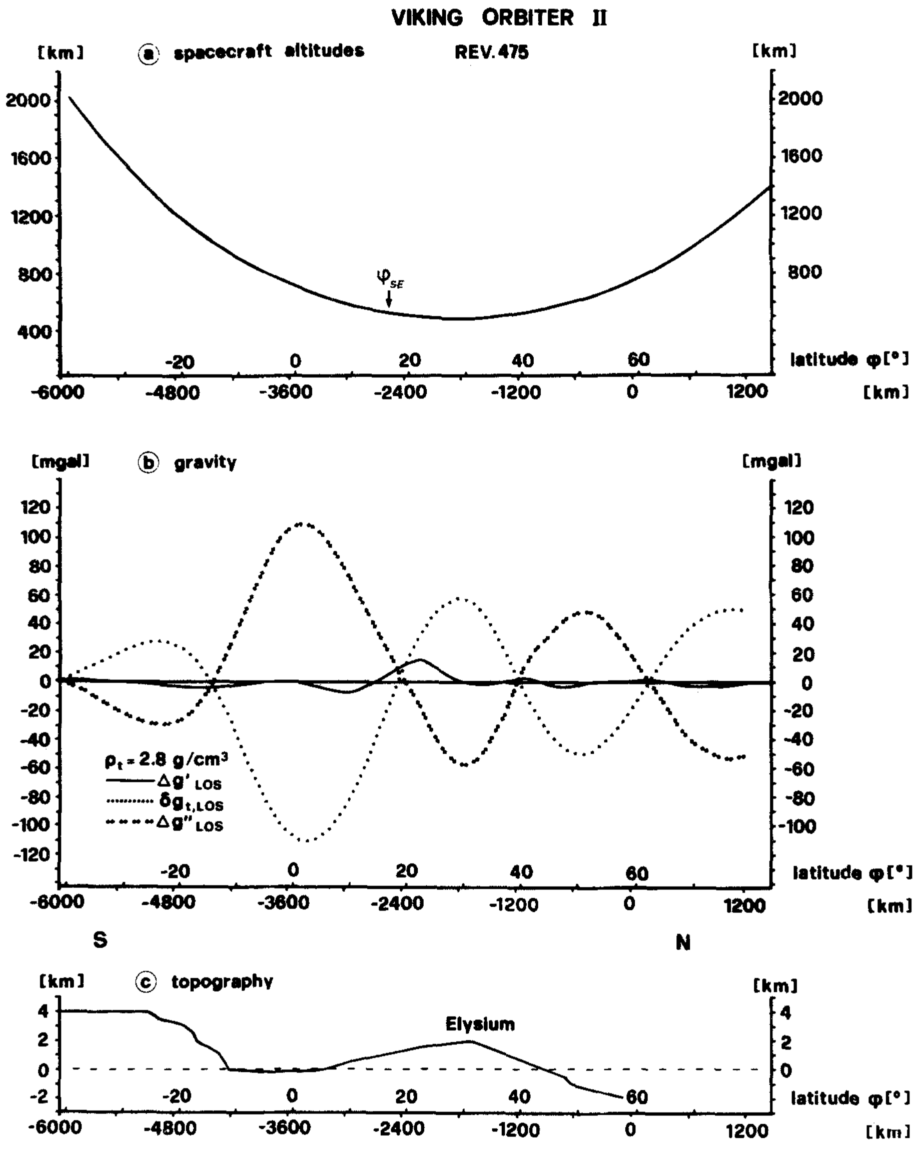

Fig. 6. Elysium dome (eastern spurs); Viking Orbiter II, Rev. 475. Detailed description see Figure 2.

Elysium root model of Janle and Ropers (1983) was necessary. This shows the consistency of their solution with a more regional one presented here.

The revolutions 511, 512, and 475 show an isostatic trend over their whole profile areas. The highlands are characterized by negative Bouguer anomalies of −45 mgal (at relative large spacecraft altitudes in this area!). The total isostatic compensation of the highlands of the model of Revolution 511 (Figure 4) is in agreement with the large age of this area of more than 4 x 10^9 y (Neukum and Hiller, 1981).

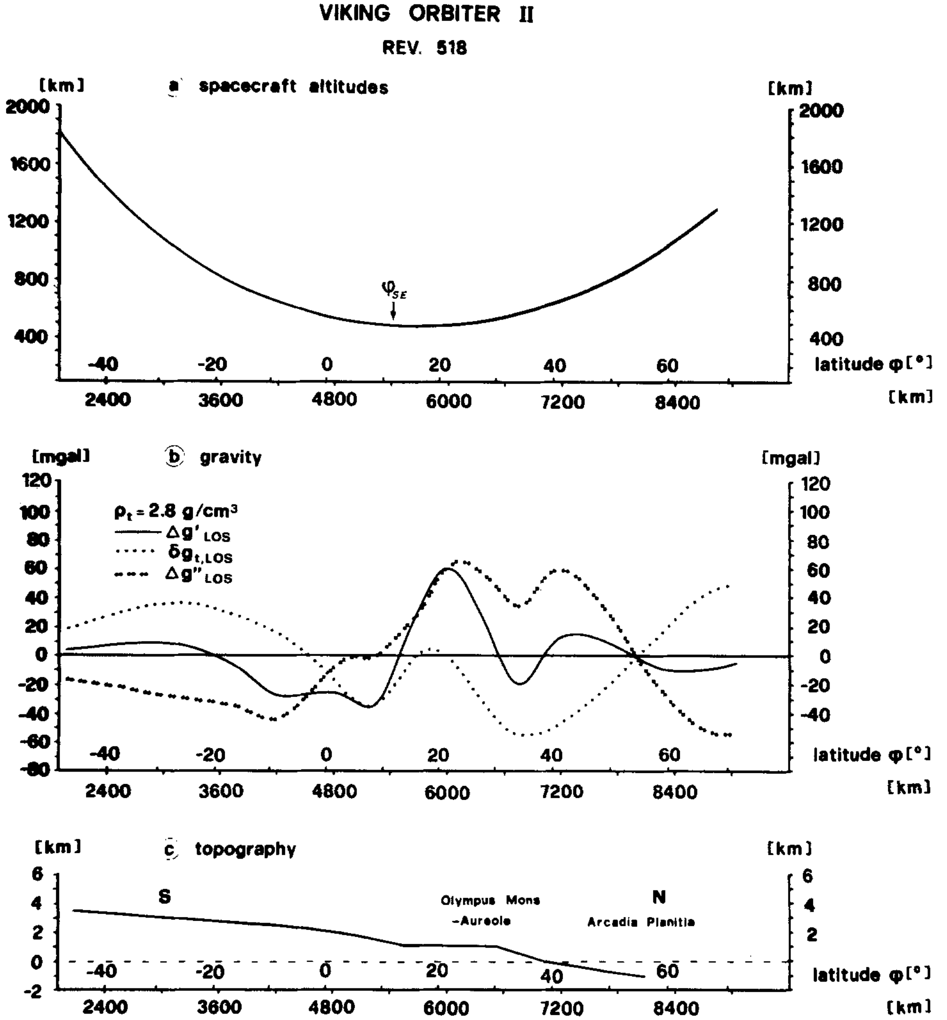

Fig. 7. Aureole region of Olympus Mons; Viking Orbiter II, Rev. 518. Detailed description see Figure 2.

The Elysium dome has a Bouguer anomaly of −120 mgal in its western highest part (Figure 4) which decreases to −58 mgal in the area of its eastern spurs (Figure 6). Thus, the whole dome shows an isostatic behaviour. This is in accordance with a detailed investigation of Janle and Ropers (1983) who found an isostatic compensation for the dome between 89 and 100%, depending on the mean crustal thickness.

The profile of Figure 7 (Revolution 518) is located in the transitional region of the Tharsis dome to the eastern and northeastern Amazonis and Arcadia Planitiae (Figure 1). Between about 20° and 35° north the aureole of Olympus Mons is crossed.

The southern highlands are again characterized by negative Bouguer anomalies with a minimum of −43 mgal. The topographic map shows that the transition to the lowlands is less steep than in the area of Elysium Planitia (Figure 1 and U.S. Geological Survey, 1976). On the other hand, the transition to positive Bouguer values in Figure 7 is at 10° N with an elevation of about 1.5 km. This transition may indicate the continental margin which is superimposed here by lava flows of the Tharsis volcanism (Scott and Tanaka, 1981) and/or by landslides of the volcanoes (Hiller *et al.*, 1982).

The area of the aureole of Olympus Mons shows a large positive free air anomaly and a local Bouguer maximum at about 22° N. This local Bouguer high could be an indication that the gravity cannot be explained from the topography alone. However, newly determined masses of the aureole of Olympus Mons are sufficient for the explanation of the gravity anomalies, as has been discussed in detail by Hiller *et al.* (1982).

4. Discussion and Conclusions

The following discussion concentrates on the highland-lowland transitional zone. Many authors demand a retreat of the highland scarp of at least several hundreds of kilometers (Scott, 1978; Hiller, 1979; Wise *et al.*, 1979). This problem is connected to the formation of the younger, topographically low northern hemisphere of Mars.

Wise *et al.* (1979) showed that surface erosion alone cannot be responsible for the formation of the lowlands because the redistribution of masses requires a minimum layer of 2 km thickness over the southern ancient highlands. They proposed a subcrustal erosion caused by mantle convection and crustal sinking as an isostatic response. Nevertheless, a resricted surface erosion in the scarp area of several hundred kilometers in horizontal direction, especially at the end of the period of the formation of the lowlands, is not in contradiction to the model of Wise *et al.*

The gravity profiles show that the change of the sign of the Bouguer anomalies correlates very well with the continental margin (Figures 2–6), i.e. surface or subcrustal erosional processes in the transition zone, if they took place, have been followed by isostatic adjustment. Figure 8 shows the Airy isostatic state of this zone. Two densities have been assumed for the upper kilometers of the highland crust: $\rho_{top} = 3.0 \text{ g cm}^{-3}$ for pure rocky material and 2.0 g cm^{-3} for a rock/ice mix. The associated isostatic crustal roots have a thickness of $t = 18$ and 12 km, respectively. This implies a subcrustal erosion of the order of 10 to 20 km associated with a downward crustal movement and/or erosion of 3 km, or an uplift of 10 to 20 km in the case of a pure surface erosion.

Both processes are in agreement with the geological evidence for the erosion of the escarpment and with the gravimetric results presented here. In the case of subcrustal erosion only a minor crustal sinking of 3 km must be considered. Pure surface erosion requires a crustal uplift and erosion of 10 to 20 km in order to reach the present state. In the case of large amounts of uplift one should expect grabens and faults in the scarp area and the forelands. These are nearly not observed. They may be superimposed by lava flows which occurred after retreat of the scarp (Scott, 1978). There should be enough

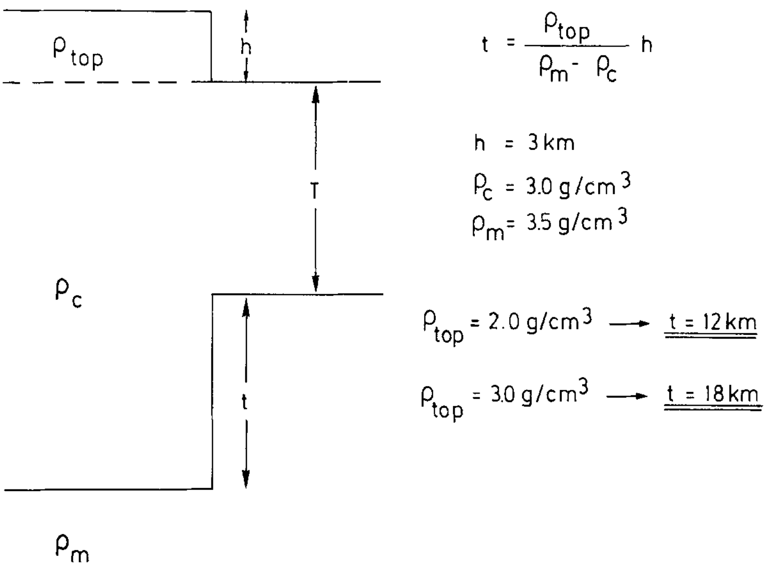

Fig. 8. Schematic sketch of the highland-lowland escarpment considering Airy compensation. ρ_{top} = density of the topography; ρ_c = crustal density; ρ_m = mantle density; T = mean crustal thickness; h = elevation of the escarpment; t = thickness of the compensating root.

time for a long-lasting uplift, because the retreat of the scarp lasted over several 10^6 y according to Neukum and Hiller (1981).

On the other hand, a very large amount of uplift and erosion of 10 km thickness or more seems to be unlikely because the foreland plains and the scarp area show remnants of highland plains (see cratered plains material (pc) and knobby material (k) of Hiller (1979)). A further problem here is again the question of the deposition of the erosional masses as in Wise *et al.* (1979). In summary, the arguments above lead to the following conclusions: the geophysical evidence of the isostatic behaviour of the transitional zone (10 to 20 km crustal thickenings in the continental areas) and geological results (remnants of ancient densely cratered regions in the lowlands, estimation of erosional masses) imply a subcrustal erosion of the forelands.

These subcrustal processes may cause an increased heat flow which could be responsible for melting of permafrost in the scarp area, retreat of the scarp and later lava flows (Scott, 1978; Neukum and Hiller, 1981). Thus, the combination of subcrustal and minor surface erosion associated with relatively small vertical isostatic movements of the crust (sinking) seems to be the best model for the retreat of the continental margin in view of geophysics and geology.

Acknowledgements

This study was sponsored by the Deutsche Forschungsgemeinschaft (German Research Society). I thank W. L. Sjogren, Jet Propulsion Laboratory in Pasadena, California, for supplying the Doppler gravity data of the Viking Orbiter II mission. I further want to thank R. Meissner and J. Voss, Kiel, for reading the manuscript and helpful discussions.

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